



Depositional architecture, provenance, and tectonic/eustatic modulation of Miocene submarine fans in the Shikoku Basin: Results from Nankai Trough Seismogenic Zone Experiment

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[1] Seismostratigraphy, coring, and logging while drilling during Integrated Ocean Drilling Program Expeditions 319, 322, and 333 (Sites C0011/C0012) show three Miocene submarine fans in the NE Shikoku Basin, with broadly coeval deposits at Ocean Drilling Program Site 1177 and Deep Sea Drilling Project Site 297 (NW Shikoku Basin). The sediment dispersal patterns have major implications for paleogeographies at that time. The oldest, finer-grained (Kyushu) fan has sheet-like geometry; quartz-rich flows were fed mostly from an ancestral landmass in the East China Sea. During prolonged hemipelagic mud deposition at C0011–C0012 (~12.2 to 9.1 Ma), sand supply continued at Sites 1177 and 297. Sand delivery to much of the Shikoku Basin halted during a phase of sinistral strike slip to oblique plate motion, after which the Daiichi Zenisu Fan (~9.1 to 8.0 Ma) was fed by submarine channels. The youngest fan (Daini Zenisu; ~8.0 to 7.6 Ma) has sheet-like geometry with thick-bedded,

coarse-grained pumiceous sandstones. The pumice fragments were fed from a mixed provenance that included the collision zone of the Izu-Bonin and Honshu Arcs. The shift from channelized to sheet-like flows was favored by renewal of relatively rapid northward subduction, which accentuated the trench as a bathymetric depression. Increased sand supply appears to correlate with long-term eustatic lowstands of sea level. The stratigraphic position and 3-D geometry of the sandbodies have important implications for subduction-related processes, including the potential for focused fluid flow and fluid overpressures above and below the plate boundary fault: In sheet-like sands, pathways for fluid flow have greater horizontal permeability compared with those in channel sands.

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1. Introduction

[2] Integrated Ocean Drilling Program (IODP) Expedition 322 represents one part of the multistage project called the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE). The fundamental goal of NanTroSEIZE is to create a distributed observatory spanning the updip limit of the seismogenic and tsunamigenic behavior along the Nankai Trough subduction boundary, positioned at a location where great earthquakes are known to occur [Tobin and Kinoshita, 2006a, 2006b]. The network of NanTroSEIZE boreholes and observatories will allow scientists to monitor hydrogeologic and geodetic behavior of the subduction megathrust and the megasplay fault (a major out-of-sequence fault seaward of the Kumano fore-arc basin), as well as the aseismic-seismic transition of the fault system. To accomplish this goal, several key components of the plate boundary system must be investigated, starting with the presubduction inputs of sediment and oceanic basement, moving landward into the shallow plate interface, and finally drilling to depths where earthquakes occur.

[3] The purpose of this paper is to document the principal deep marine clastic systems (submarine fans) discovered during IODP Expedition 322 that accumulated in the northern Shikoku Basin during the middle and late Miocene and to interpret their evolution in the context of the likely plate tectonic framework at that time.

[4] A better understanding of the lithostratigraphic units, how they were deposited, and their networks of sediment dispersal is important for deductions regarding parameters that affect fault slip behavior. The stratigraphic architecture of sandbodies, for example, may influence where fluid flow is focused (e.g., through high-permeability sheets or meandering shoestrings) and where excess pore water pressure might build up (e.g., at lateral pinch-outs of depositional lobes) [Bredhoeft *et al.*, 1988; Underwood, 2007]. At the same time, the depositional setting of the Shikoku Basin is unusual from the global perspective of marine sedimentology because the basin formed on the back-arc side of an intraoceanic subduction zone (Izu-Bonin), but strata are subducting beneath a continental arc: It is more typical to find subduction only in the fore-arc setting. The basin's history of sedimentation, therefore, has been affected by a combination of basement relief, volcanic activity along two sides of the basin, reorganization of the plate boundary, episodes of collision between the Izu-Bonin and SW Japan (Honshu) Arcs, and subduction-driven uplift of the Japanese hinterland [Underwood and Fergusson, 2005; Ike *et al.*, 2008a, 2008b]. This complexity sets the subduction inputs to the Nankai Trough apart from such examples as the Cascadia Basin and the Chile Trench, where subduction occurs only in the fore-arc region [Underwood and Moore, 1995; Underwood, 2007]. It also challenges the generic paradigm of progressive thickening and coarsening upward as the subducting oceanic plate

moves closer to the subduction front [Piper *et al.*, 1973], because the incoming plate already contains a thick pile of coarse clastics before entering the trench environment.

[5] Another question to consider when attempting to understand the stratigraphy of subduction inputs is whether or not the effects of eustatic sea level fluctuations [cf. Haq *et al.*, 1987] can be recognized through the strong overprints of local and regional tectonics. If so, then some of the simple expectations regarding facies relations in ancient subduction complexes need to be broadened.

2. Origin of the Shikoku Basin

[6] The Shikoku Basin lithosphere formed due to back-arc rifting and seafloor spreading in the eastern part of the Philippine Sea plate between 30 and 15 Ma [Watts and Weissel, 1975; Kobayashi and Nakada, 1979; Taylor, 1992; Okino *et al.*, 1999; Sdrolias *et al.*, 2004]. The Kyushu-Palau Ridge separates the young Shikoku Basin (eastern Philippine Sea plate) from the 40 to 60 Ma West Philippine Basin (western Philippine Sea plate) lithosphere. The Kyushu-Palau Ridge is a remnant Eocene-Oligocene arc that split away from the Izu-Bonin-Mariana Arc during Shikoku Basin rifting. These tectonic events influenced the position and nature of the triple junction between the Pacific plate, Philippine Sea plate, and Eurasian plate (or Amurian subplate). The Kinan seamount chain represents the vestiges of the extinct spreading center in the Shikoku Basin.

[7] The Neogene history of the Shikoku Basin has been interpreted by Kano *et al.* [1991] and Taira [2001] to have involved six main tectonic events: (1) rifting of the paleo-Izu-Bonin Arc and opening by seafloor spreading of the Shikoku Basin (25 to 15 Ma), (2) rifting of the paleo-SW Japan (Honshu) continental arc and spreading of the Japan Sea basin (22 to 15 Ma), (3) widespread, near-trench igneous activity 17 to 12 Ma in SW Honshu, (4) initiation of subduction of the Philippine Sea plate and collision of the Izu-Bonin Arc against the SW Japan (Honshu) Arc at 15 Ma, (5) a main phase of subduction of the Philippine Sea plate beginning at 8 Ma, and (6) collision of the Kuril fore-arc sliver and formation of the Hidaka mountain belt beginning at 15 Ma. Kimura *et al.* [2005] provided a detailed summary of the Tertiary magmatic processes linked with the plate tectonic history of the SW Japan (Honshu) Arc. They broadly followed the interpretations of Taira [2001], also invoking

Paleogene subduction of the Kula and Pacific plates beneath the eastern margin of Eurasia, followed by a brief episode of transform faulting to allow the Shikoku Basin to open at 27 to 15 Ma. Kimura *et al.* [2005] also reiterated evidence for subsequent opening of the Japan Sea back-arc basin in middle Miocene time [e.g., Otofugi *et al.*, 1985], which caused Japan to break away from Eurasia, and SW Japan rotated clockwise $\sim 45^\circ$ as it drifted south (17 to 15 Ma). Southward drift required subduction of the Philippine Sea plate beneath SW Japan, leading to the formation of a magmatic arc, with subduction of the hot Shikoku Basin lithosphere and spreading ridge resulting in anomalous near-trench volcanism between 17 and 12 Ma [Hibbard and Karig, 1990].

[8] Recent plate tectonic reconstructions by Mahony *et al.* [2011], which use the published finite rotation poles from Gaina and Müller [2007] for the Philippine Sea plate relative to Eurasia for the past 15 Ma, are incorporated into this paper. They suggest that prior to 15 Ma, the Pacific plate subduction dominated Kyushu tectonics and that from 15 to 6 Ma, the evolving relative plate motions shifted the triple junction between the Pacific plate, Philippine Sea plate, and southwest Japan northward, so that the Philippine Sea plate was subducted beneath Kyushu. The lack of subduction-related volcanism on Kyushu from 10 to 6 Ma was attributed to shallow subduction of the young Shikoku Basin lithosphere. By at least 6 to 5 Ma, changes in the Philippine Sea plate motion led to more rapid, nearly trench normal, subduction beneath Kyushu. Their model also favors the initial collision between the Izu-Bonin Arc with the SW Japan (Honshu) Arc occurring at ~ 8 to 6 Ma, rather than the more widely accepted date of ~ 15 Ma [e.g., Tamura *et al.*, 2010; Tani *et al.*, 2010; Yamazaki *et al.*, 2010]. The plate reconstructions and computer simulations of Hall [2002, 2012] also show considerable left-lateral (and strike slip) motion and collision of the Izu-Bonin and Honshu Arcs between 10 and 5 Ma. There does, however, appear to be compelling evidence for collision and accretion of some crustal block at about 15–17 Ma associated with Mio-Pliocene sedimentary basins forming in the Izu-Honshu collision zone [e.g., Soh *et al.*, 1991] and the intrusion of the Kofu granitic complex and Tanzawa tonalite [Tamura *et al.*, 2000; Tani *et al.*, 2010]. Perhaps, this was not the Izu-Bonin Arc in a strict sense but either a noncontiguous, possibly younger, volcanic arc or some other bathymetric high [cf. Ali and Moss, 1999; Takahashi and Saito, 1997]. Others have proposed a separate “Mineoka plate” to account for the obduction of the

Mineoka ophiolite immediately prior to Izu-Honshu Arc collision [Ogawa *et al.*, 1985; Ogawa and Taniouchi, 1988]. It is interesting to note that the present northern part of the Izu-Bonin Arc contains ~50 Ma arc crust, perhaps suggesting that it may include the remnants of such a ridge that collided at ~15–17 Ma.

[9] Regardless of the details, reorganization of the plate boundary must have influenced rates and pathways of sediment delivery throughout the regional system, including the Shikoku Basin. Coring during Expedition 322 provided a wealth of new evidence to improve such reconstructions. Sediments of the Shikoku Basin and Nankai trench wedge are particularly important because they are the inputs to the Nankai subduction factory [Underwood, 2007]. Significant along-strike variations in lithostratigraphy can be seen by comparing stratigraphic sections at Site 1177 (Ashizuri transect); Sites 1173, 1174, and 808 (Muroto transect); and Sites C0011 and C0012 (Kumano transect). As such, changes in lithology, mineralogy, geochemistry, and 3-D facies architecture will influence the mechanical and hydrogeological behavior of the accretionary prism and the plate boundary fault. Better predictions about the types and distribution of lithologies

at depth contribute to improved forecasting of fluid pathways and fluid pressures within the offscraped and subducting sedimentary units. This paper concentrates on sandy turbidite sedimentation during the Miocene. Those deposits possess the greatest likelihood for directing fluid flow through high-permeability conduits.

3. Methods

[10] In this paper, we present an overview of the sedimentology and lithostratigraphy from IODP Sites C0011 and C0012, supplemented with Deep Sea Drilling Project (DSDP)/Ocean Drilling Program (ODP)/IODP drill sites in the vicinity (Figure 1). Specifically, we have used the sediment petrography, age data based on micropaleontology and paleomagnetism, stratigraphy, and logging while drilling (LWD) data from these drill sites, together with seismic profiles that cross Sites C0011 and C0012 [Underwood *et al.*, 2010; Expedition 333 Scientists, 2011]. Older stratigraphic data are from DSDP Site 297 [Harrold and Moore, 1975; Karig *et al.*, 1975] and ODP Site 1177 [Moore *et al.*, 2001a]. These four locations are

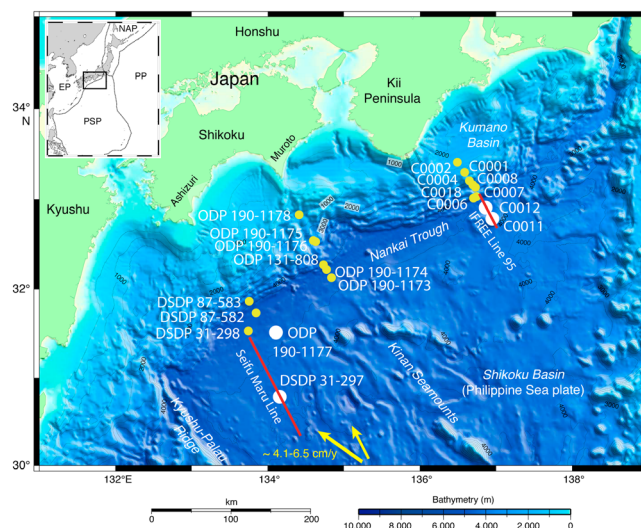


Figure 1. Bathymetric map, Nankai Trough off SW Japan showing position of DSDP/ODP/IODP sites. Sites referred to in this paper (C0011, C0012, 1177, and 297) are shown with a larger white dot. Arrow = convergence direction between Philippine Sea plate and Japan. Previous transects of Nankai Trough were positioned off Ashizuri and Muroto Peninsulas of Shikoku. EP = Eurasian plate; PP = Pacific plate; PSP = Philippine Sea plate; NAP = North American plate. Contours are in meters below sea surface. Red line shows Line 95 from Institute for Frontier Research on Earth Evolution (IFREE) mini-3-D seismic survey [Park *et al.*, 2008], interpreted in Figure 4a, and Seifu Maru seismic line [after Karig *et al.*, 1975, Figure 6]. The Kinan seamount chain represents the approximate axis of the extinct spreading center in the Shikoku Basin and divides it into western and eastern sectors. Ashizuri, Muroto, and Kii Peninsulas are shown, from which the three corresponding drill transects approximately orthogonal to the Nankai Trough axis are named.

the only drill sites for which Shikoku Basin in situ data exist. We note that age dating for DSDP Site 297 and ODP Site 1177, however, is relatively poor when compared with that from IODP Sites C0011 and C0012. Detailed methods for all relevant shipboard analyses are described by *Expedition 322 Scientists* [2010].

4. IODP Expeditions 322 & 333

[11] IODP Expeditions 322 and 333 were designed to document the characteristics of the incoming sedimentary strata and upper igneous basement prior to their arrival at the subduction front [Saito *et al.*, 2009; Underwood *et al.*, 2010; *Expedition 333 Scientists*, 2011]. During IODP Expedition 322, coring was conducted at two sites in the Shikoku Basin on the subducting Philippine Sea plate (Figure 1). Site C0011 is located on the northwest flank of a prominent bathymetric high, the Kashinosaki Knoll, and Site C0012 is located near the crest of the knoll. Kashinosaki Knoll is located ~100 km southeast of the Kii Peninsula and is ~150–200 km west of the Izu-Bonin Arc [Ike *et al.*, 2008a]. When seamounts and other bathymetric highs are subducted, they can cause significant deformation of the overriding plate and may act as asperities deeper in the seismogenic zone [Cloos, 1992; Scholz and Small, 1997; Bilek *et al.*, 2003; Bilek and Lay, 2002]. When Kashinosaki Knoll collides with the accretionary prism in about 1 Myr, the associated variations in sediment type and thickness from flanks to summit will likely result in local variations in prism deformation [Ike *et al.*, 2008a]. Due to operational failures and insufficient allocation of drilling time, Expedition 322 recovered an incomplete stratigraphic record from Sites C0011 and C0012. Intervals of the upper Shikoku Basin were cored using hydraulic piston coring system (HPCS) during Expedition 333 [*Expedition 333 Scientists*, 2011]. LWD was conducted at Site C0011 using contingency time during IODP Expedition 319, immediately prior to Expedition 322 [Saffer *et al.*, 2009].

5. Lithologic Units

[12] Five lithologic units were identified at Site C0011 and six at Site C0012, based on sediment composition, sediment texture, and sedimentary structures [Underwood *et al.*, 2010; *Expedition 333 Scientists*, 2011]. Unit I (Figure 2 and Table 1) consists of silty clay with intercalations of fine to coarse volcanic ash, typically with unaltered glass shards. The hemipelagic/pyroclastic facies ranges in age

from Quaternary to late Miocene (0 to ~7.8 Ma). Strata at Site C0012 were divided into three subunits by *Expedition 333 Scientists* [2010] on the basis of variations in lithification, alteration, and abundance of discrete volcanic ash layers (Figure 2). The deposition of Unit I occurred predominantly by hemipelagic settling of suspended sediment [*Expedition 333 Scientists*, 2010].

[13] An abrupt change in lithology occurs at ~347 meters below seafloor (mbsf) (C0011) and ~150 mbsf (C0012) with the appearance of tuffaceous sandstone and heterolithic gravel and sandstone. This change marks the Unit I/II boundary. Unit II (Figure 2 and Table 1) is characterized by coarse beds with sharp and well-defined upper and lower boundaries, separated by indurated mudstone. Unit II is late Miocene in age (~7.6 to 9.1 Ma at C0011 and ~7.8 to 9.4 Ma at C0012). Point counts within these sandstone packages show that pyroclasts, magmatic crystals, and volcanoclastics prevail over sedimentary and metamorphic rock fragments and detrital minerals (Figure 3). The upper package (Unit IIa) at Site C0011 (340–377 mbsf) contains tuffaceous sandstones, whereas the lower sand-rich interval (Unit IIb, 377–479 mbsf) contains volcanoclastic sandstone and dark gray siltstone [Underwood *et al.*, 2010]. The distinction between tuffaceous and volcanoclastic sandstones is based on the abundance of pumice and volcanic glass shards (Figure 3). The tuffaceous sandstones are composed of >25% pyroclasts, with magmatic minerals showing relative abundances of plagioclase > pyroxene > amphibole. The volcanic glass appears very fresh, with pumiceous glass as the dominant component. The siliciclastic component is mainly chert, altered tuff, siltstone, and sandstone. The volcanoclastic sandstones contain >25% volcanoclastic grains and <25% pyroclastic grains. These sandstones have large proportions of minerals, with relative abundances of plagioclase > pyroxene > quartz > amphibole. The quartz content is typically between 2% and 6%, most of which is chert. Additionally, there are large amounts of sedimentary lithic grains (siltstone, sandstone, and chert).

[14] Unit II also contains chaotic intervals, or mass transport deposits (MTDs), of intermixed volcanoclastic sandstone and bioturbated silty claystone. At Site C0012 (Figure 2 and Table 1), two MTDs were recovered that are 0.3 and 3.1 m thick (150.86–151.17 and 178.00–181.10 mbsf). The broken strata occur with folding, thinning, and attenuation of primary bedding, probably deformed by gravitational sliding on the relatively steep north facing slopes of the Kashinosaki Knoll.

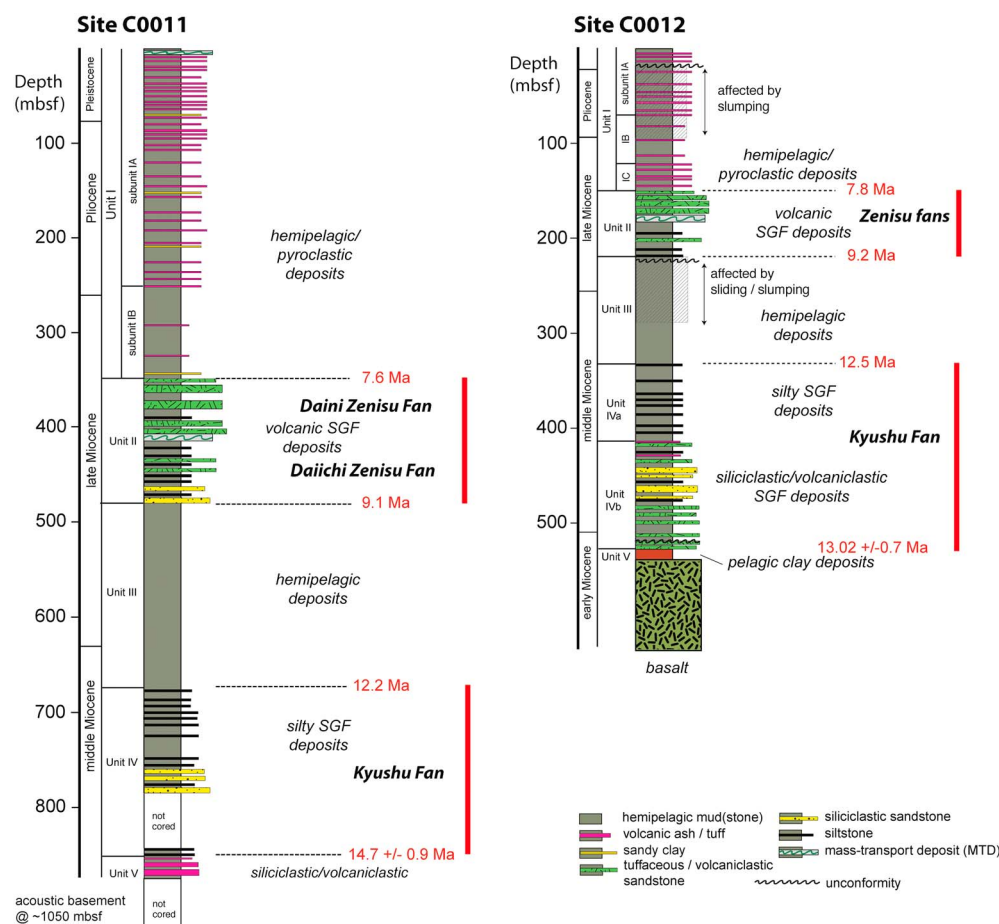


Figure 2. Lithologic columns for IODP Sites C0011 and C0012 drilled in the vicinity of Kashinosaki Knoll, NE Shikoku Basin, showing IODP Sites C0011 and C0012, based on results from Expeditions 322 and 333 [Underwood *et al.*, 2010; Expedition 333 Scientists, 2011]. See text for explanation of the Kyushu and Zenisu submarine fans. SGF = sediment gravity flow, including turbidity current. Also, see Table 1 for summary of lithologic units. Note, at Site C0012, unlike at Site C0011, the two Zenisu Fans are not separately defined.

Smear slide petrography demonstrates that the sandstone fragments in the MTDs are mixtures of primary eruptive products and reworked pyroclastic and sedimentary rock fragments [Underwood *et al.*, 2010].

[15] Unit III (Figure 2 and Table 1) is a hemipelagic facies characterized by bioturbated silty claystone. Secondary lithologies include lime mudstone and calcareous claystone. The mudrocks are middle-late Miocene in age (~9.1–12.2 Ma at C0011 and ~9.4–12.7 Ma at C0012), and the unit thins from 194.92 m at Site C0011 to 112.00 m at Site C0012. At Site C0012, the deposits include an interval at least 15.2 m thick with steeply inclined bedding, typically at an angle of 40° to 45°. From seismic evidence and core-scale deformation structures at Site C0012, this disruption appears to be associated with rotational normal faulting on the north inclined flank of Kashinosaki Knoll.

Nannofossil datums also suggest an angular unconformity near the top of this interval with a hiatus of ~1 Myr. The rate of hemipelagic sedimentation (uncorrected for compaction) at Site C0011 changed from 3.9 m/kyr to 7.7 m/kyr at ~11 Ma [Underwood *et al.*, 2010].

[16] The lower boundary of the hemipelagic facies is defined by the appearance of dark gray clayey siltstone (mud turbidites). Unit IV (Figure 2 and Table 1) consists mainly of bioturbated mudstone with interbeds of normally graded siltstone and fine-grained siliciclastic sandstone. Wood fragments are common, as are detrital grains of polycrystalline quartz and metamorphic rock fragments. Unit IV is middle Miocene in age (~12.2–14.0 Ma at Site C0011 and >12.7–13.5 Ma at Site C0012). This interval thins out against the flanks of Kashinosaki Knoll (Figure 1). The coarser interbeds are interpreted as sediment gravity flow (SGF) deposits (e.g., turbidites;

Table 1. Lithologic Units at Sites C0011 and C0012

Lithologic Unit	Unit Name	Depth CSF m ^a	Thickness ^a (m)	Age ^a	Dominant Lithology	Minor Lithology
Unit Ia Unit Ib	Upper Shikoku Basin	0.00–251.56 251.56–347.82	340 150.86	Holocene-late Miocene 0–7.6 Ma 0–7.8 Ma	Silty clay(stone) Mudstone	Ash
Unit IIa Daimi Zenisu Fan	Middle Shikoku Basin tuffaceous sandstones	347.82–479.06	139.06 68.95	Late Miocene 7.6–9.1 Ma 7.8–9.4 Ma	Silty claystone	Tuffaceous sandstone
Unit IIb Daiichi Zenisu Fan	Volcaniclastic sandstones	150.06–219.81				Tuffaceous sandstone Volcaniclastic sandstone Clayey siltstone Calcareous claystone Lime mudstone
Unit III	Lower Shikoku Basin hemipelagites	479.06–673.98 219.81–331.81	194.92 112	Late-middle Miocene 9.1–12.3 Ma 9.4–12.7 Ma	Silty claystone Silty claystone	
Unit IV Kyushu Fan	Lower Shikoku Basin sediment gravity flow deposits	673.98–849.95 331.81–415.58	175.97 83.77	Middle Miocene 12.3–13.9 Ma 12.7–13.5 Ma	Tuffaceous silty claystone Silty claystone clayey siltstone	Silty sandstone Siltstone
Unit V	Volcaniclastic-rich	849.95–876.05 415.58–528.51	>26.10 ^a 112.93	Middle Miocene >13.9 Ma 13.5 to >18.9 Ma	Tuffaceous sandy claystone Silty claystone Sandstone (including volcaniclastic)	Silty claystone Tuff layer Tuff
Unit VI	Pelagic claystone	Not drilled 528.51–537.81	Not drilled 9.3	Early Miocene >18.9 Ma	Red calcareous claystone Basalt	
Unit VII	Basement	Not drilled 537.81–576.00	Not drilled 38.2 drilled	Early Miocene >18.9 Ma		

^aIn this table, apart from Unit I (Expedition 333 data), paired depth, thickness, and age data are read as Site C0011 = upper line and Site C0012 = lower line. CSF m = depth in meters cored from seafloor.

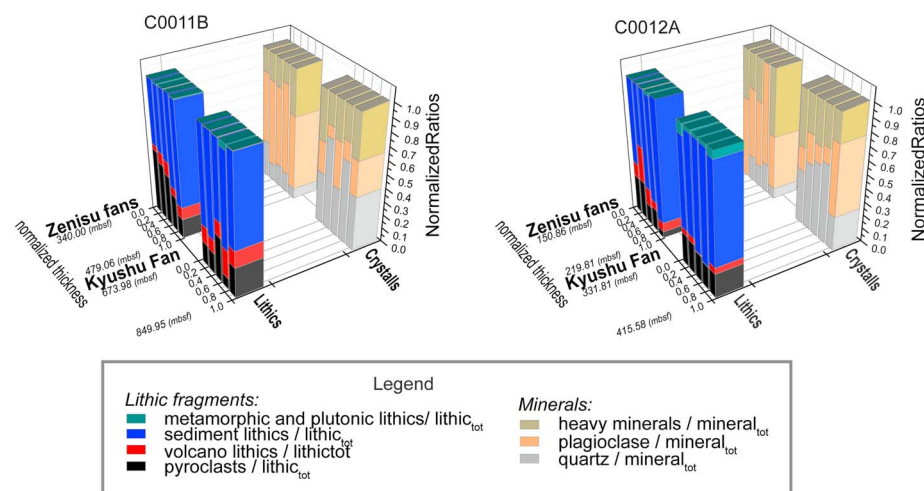


Figure 3. Summary petrography of volcanic sandstones to show different compositions of Kyushu and Zenisu Fan sandstones at both Sites C0011 and C0012. Raw data for these plots are provided in the supporting information. See Figure 2 for stratigraphic position of the submarine fans.

see *Middleton and Hampton* [1973] for definition of SGF deposits).

[17] Unit V (Figure 2 and Table 1) consists of tuffaceous sandy mudstone and sandstone, with minor amounts of tuff. Because of poor recovery and technical failures at Site C0011, the age of Unit V is poorly constrained within the middle Miocene. The correlation of units from flank to crest of Kashinosaki Knoll is further complicated by the occurrence of a major unconformity (see below). Fission track data suggest that detrital source rocks for the top of the Unit V at Site C0011 were 14.7 ± 0.9 Ma, whereas detrital sources for the base of Unit V at Site C0012 were 13.02 ± 0.7 Ma (Saito, unpublished data). Evident from major element compositions (supporting information)¹, the tuffs at Site C0011 are chemically correlative with the thick rhyolitic tuffs that were recovered at Site 808 from beneath the toe of the accretionary prism along the Muroto transect of the Nankai Trough (Figure 1); those strata yielded an age of ~ 13.6 Ma [Taira *et al.*, 1992]. The fission track data suggest that the detrital sources for the upper deposits of Unit V (Site C0011) were older than the source rocks that supplied sediment to the base of Unit V as originally defined at Site C0012, suggesting that strata of Unit V (defined at Site C0011) are actually completely missing at Site C0012 (Figure 2 and Table 1). These revised age dates are sensible considering that Unit V at Site C0011 (= seismic unit “F” reported in *Underwood et al.*, [2010]) abuts on a normal fault at the northern edge of the

Kashinosaki Knoll, and seismic unit F is missing on the knoll. Therefore, Unit IV at Site C0011 is equivalent to both Unit IVa and Unit IVb at Site C0012 (Figure 2 and Table 1). Heavy mineral composition shows a “Kumano component” (biotite, garnet, zircon, and apatite) in Unit IV at Site C0011 and Units IV + V at Site C0012 but a different, but unknown, source only in Unit V at Site C0011. Thus, we have merged Units IV and V as originally defined by *Underwood et al.* [2010] into Unit IV for Site C0012 (Figure 2 and Table 1).

[18] At Site C0012, an angular unconformity occurs at ~ 510 mbsf, with an apparent hiatus of ~ 4 Myr (Figure 2). Sandstones above the unconformity, some of which show cross laminae, plane-parallel laminae, convolute laminae, and soft sediment sheath folds, appear to have two separate detrital provenances: (1) a volcanic source with fresh volcanic glass, together with relatively large amounts of feldspar, and (2) a siliciclastic source enriched in sedimentary lithic grains, quartz, and heavy minerals (including pyroxene zircon and amphibole) (supporting information). Bulk X-ray diffraction (XRD) confirms that relative percentages of quartz and feldspar increase in the coarse-grained strata, and XRF data show appreciable scatter in most of the major oxides because of lithologic/textural heterogeneity. These sandstones are probably equivalent to those of Unit IV at C0011. Their ranges of compositions, textures, and ages are also reminiscent of those of the Miocene sand layers and volcanoclastic-rich deposits at ODP Site 1177 [Moore *et al.*, 2001b; Fergusson, 2003; Underwood and Fergusson, 2005] (Figure 1).

[19] The lowermost sediments were not cored or logged at C0011, but at Site C0012, Unit VI

¹Additional supporting information may be found in the online version of this article.

(Figure 2 and Table 1) consists of a 9.3 m thick interval of variegated red, reddish-brown, and green calcareous claystone, rich in nannofossils, with minor amounts of radiolarian spines. Carbonate content in Unit IV is ~20 wt % based on bulk powder XRD analysis. These pelagic sediments are early Miocene in age (>18.9 Ma). The pelagic claystones accumulated in direct contact with igneous basement, and their mottled red-green coloration is probably due to iron reduction. On the basis of the nannofossils in the claystone, the Kashinosaki Knoll basaltic basement is older than 18.9 Ma.

6. Seismic Stratigraphy

[20] *Ike et al.* [2008a, 2008b] used seismic data to map the 3-D seismic facies distribution tied with ODP drill cores to document regional and local variations in basement relief, sediment thickness, and sediment type in the Shikoku Basin. Their trench-parallel seismic profiles showed three regional provinces in the Shikoku Basin that can be distinguished by the magnitude of basement relief and sediment thickness: designated western (<200–400 m basement relief, >600 m sediment

thickness), central (>1500 m relief, ~2000 m sediments), and eastern (<600 m relief, ~1200 m sediments) provinces. The total thickness of sediment in basement lows is as much as six times greater than that over basement highs.

[21] The thicker accumulations of sediments (~1200 m) over and around Kashinosaki Knoll [cf. *Ike et al.*, 2008a] were confirmed by core-log-seismic integration during IODP Expedition 322 (see figures F6 for Site C0011 and F34 for Site C0012). Figure 4a shows a line from the seismic reflection survey of *Park et al.* [2008] that crosses Sites C0011 and C0012 (Figures 4b and 4c show details discussed below). The lower portion of the sedimentary section has a package of high-amplitude, continuous reflections (Figure 4a), shown by coring to include sediment gravity flow deposits (e.g., turbidites). Those intervals lap onto steep basement slopes but are parallel to the gentler basement slopes. The total sediment thickness on the western and northern slopes is ~40–50% more than that on the summit and southeastern slopes of Kashinosaki Knoll. From these characteristics, we infer that the basal sedimentary section northwest of Kashinosaki Knoll accumulated by deposition from larger-

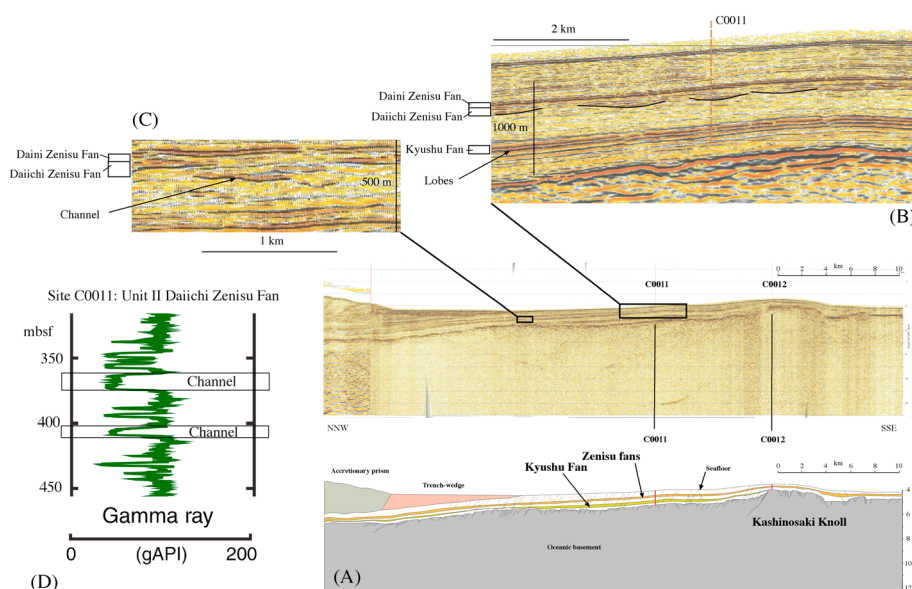


Figure 4. (a) Spliced composite seismic profile of a representative depth section from NanTroSEIZE 3-D data volume [Moore, 2009] and Line 95 from IFREE mini-3-D seismic survey [Park et al., 2008] that crosses Sites C0011 and C0012, and interpretation of main lithostratigraphic units. Enlargements of seismic sections show diagnostic depositional environments for the Kyushu and Zenisu submarine fans along this transect, including (b) sheet-like seismic character of Unit IV (Kyushu Fan), interpreted as distal outer fan lobe deposits, and (b and c) irregular seismic character of Unit IIB (Daiichi Zenisu Fan), interpreted as mainly volcanic sandstone filled, including MTD, submarine channel deposits, immediately overlain by a continuous, high-amplitude, seismic interval (Unit IIA), interpreted as unconfined, sheet-like volcanic sandstone deposits. (d) Logging while drilling (LWD) data show 10 to 20 m thick blocky gamma ray motif typical of many submarine channel fills.

volume sediment gravity flows, such as turbidity currents, whereas the area southeast of Kashinosaki Knoll was dominated by hemipelagic sedimentation over asymmetric basement relief.

[22] The intervals with semitransparent to weak reflections (Figure 4a) correspond to mudstones that we interpret to originate from dilute hemipelagic suspensions (for example, Unit III hemipelagic facies). Of particular interest are the differences in acoustic character caused by intervals of sandy sediment gravity flow deposits. The cores and LWD data confirm that one interval of strong seismic impedance contrasts matches the coarse clastics of subunit IIb. The blocky log response (Figure 4d) and discontinuous reflector geometries (Figures 4b and 4c) are suggestive of submarine channels. We refer to that sandbody as the Daiichi Zenisu submarine fan, with channels on the order of 10 to 20 m in depth and 800 to 1000 m in width, similar in dimensions to many modern and ancient submarine channels [Clark and Pickering, 1996]. The basal part of the thickest channel fill consists of an ~10 m thick MTD (400.86 to 411.15 mbsf at C0011). This chaotic deposit contains disaggregated pieces of volcanoclastic sandstone and bioturbated mudstone that show tight to isoclinal folding, thinning and attenuation of bedding, and subhorizontal small-scale faults with a normal (extensional) sense of displacement in the uppermost part. Interpretations of the seismic data suggest that these MTDs were erosive and responsible for channel incision (Figures 4b and 4c). The map view channel orientation remains uncertain, something that cannot be resolved without a more extensive 3-D seismic grid. The features observed in Line 95 could be relatively straight channels coming from the east-northeast (subparallel to the trend of the trench axis) or sinuous channels coming from the north. This acoustic interval thins to the south but continues over the crest of Kashinosaki Knoll.

[23] Two additional distinct intervals of high-amplitude reflections are more continuous when compared to Daiichi Zenisu Fan, suggestive of sheet-like flows. We refer to the youngest nonchannelized sandbody as the Daini Zenisu Fan. That relatively thin packet of reflections matches the coring interval with distinctive tuffaceous sediment gravity flow deposits (subunit IIa) and likewise continues over the crest of the basement high. The older interval of silty sediment gravity flow deposits (Unit IV) is also sheet-like (Figure 4), with an acoustic geometry suggestive of distal submarine fan (lobe and lobe fringe) deposits [e.g., Deptuck et al., 2008]. We designate Unit IV as the Kyushu Fan, and its equivalent packet of prominent reflections loses continuity near the edge of Kashinosaki Knoll. Unit IV

appears to thin out almost completely against basement relief approximately 8–9 km north of Site C0011, but it may correlate with weak reflections observed under the trench wedge (Figure 4a). This geometry for the Kyushu Fan, showing thinning and onlap to both the south and north, suggests that it might have been supplied by sediment gravity flows moving oblique to the seismic line and infilling preexisting basement topographic lows, i.e., from a more westerly or easterly direction.

[24] The presence of sandbodies above Kashinosaki Knoll is interesting and perhaps surprising, because the thinning and onlap of older units against the knoll suggest that it was already an existing seafloor high [Ike et al., 2008a]. This observation requires either upslope flow [cf. Muck and Underwood, 1990; Pickering et al., 1992] or postdepositional uplift of the basement high. In contrast, Unit IV shows a substantial thinning toward Kashinosaki Knoll (also recognized by Ike et al. [2008a, Figure 4]) where it completely disappears on the downthrown side of a normal fault. This suggests that Kashinosaki Knoll had significant seafloor relief at least as early as the middle Miocene when the sediment gravity flow deposits of Unit IV began accumulating (i.e., ~14.0 to 13.5 Ma). Also, the thinning out of Kyushu Fan against Kashinosaki Knoll and the continuity of the Zenisu Fan over the top, but not as horizontal bedding, favor tectonic rejuvenation and uplift of the knoll (estimated at ~300 m of vertical uplift), probably in response to compressive forces as it approached the Nankai Trough.

7. Detrital Provenance

[25] Based on geographic proximity, the potential provenance of the sandstones in both the Kyushu and Zenisu Fans could be one or more of the following: SW Japan Arc to the north, Izu-Bonin Arc to the east, and for Unit II the Izu-Honshu Collision Zone. Plate tectonic reconstructions by Mahony et al. [2011] for the Shikoku Basin suggest that a considerable amount of sinistral strike slip associated with oblique subduction may have taken place during the late Miocene (see below), which opens up the intriguing possibility that many of the terrigenous sands were derived from a now-eroded landmass in the East China Sea prior to and during opening of the Sea of Japan. Westward continuation of the tectonostratigraphic belts of SW Japan (e.g., Shimanto, Sambagawa, and Ryoke belts) from Kyushu, via the Okinawa Islands, to north of Taiwan has been documented, for example, by Isozaki et al.

[2010, Figures 1 and 10]. The sandy detritus in Kyushu Fan was likely eroded from sources similar to those of the Outer Zone of southwest Japan [e.g., Taira *et al.*, 1989; Nakajima, 1997].

[26] Superficially similar sand deposits to those encountered at Sites C0011 and C012, and with overlapping ages, have been documented on the west side of the Shikoku Basin at ODP Site 1177 (Figure 5a) and DSDP Site 297 (Figures 5b and 6) [Karig *et al.*, 1975; Harrold and Moore, 1975; Marsaglia *et al.*, 1992, 1995; Fergusson, 2003; Underwood and Fergusson, 2005]. That Miocene dispersal system spread quartz-rich terrigenous sediment over a broad area of the Shikoku Basin [Moore *et al.*, 2001; Fergusson, 2003]. Sand and sandstone samples from Site 1177 (occurring in four sandy intervals within Unit III; Fig. 5a), within the lower-upper Miocene lower Shikoku Basin deposits, typically contain 36%–47% quartz, 20%–30% feldspar, and 22%–43% lithic fragments [Fergusson, 2003]. Lithic fragments are dominantly of sedimentary type with a smaller quantity of silicic volcanic rock fragments (2%–5%).

[27] At Site 297, a 247 m thick unit of sandy sediment gravity flow deposits was penetrated from 330 to 570 mbsf (Figure 6). The age dating is relatively poor without continuous coring but suggests late middle Miocene to early Pliocene ages [Karig *et al.*, 1975]. The composition of 28 sandstone

samples averages $\text{quartz}_{14}\text{feldspar}_{15}\text{lithics}_{71}$ [Harrold and Moore, 1975]; the lithic fragments are predominantly sedimentary rock fragments, and the volcanic/lithic (V/L) ratio is quite low with an average of 0.09 ($\sigma=0.10$). These sedimentary rock fragments are predominantly well rounded, equant to elongate grains containing quartz and feldspar in an argillaceous matrix. Mica, plant debris, and metamorphic grains are also present (polycrystalline quartz grains; probably metasedimentary). The low V/L ratio, the high percentage of sedimentary rock fragments, and the presence of plant debris indicate that the sands were eroded from a continental source area with sedimentary parent rocks.

[28] Cessation of anomalous near-trench volcanism at ~11 Ma [Kimura *et al.*, 2005] and subsequent erosion into the plutons and accreted sedimentary rocks resulted in a gradual change from smectite- to illite-dominated clay mineral assemblages [e.g., Underwood and Fergusson, 2005; Guo and Underwood, 2012]. This temporal change in mineralogy supports an interpretation that a mainland terrigenous source provided substantial volumes of fine-grained sediment to these sites, even though the Izu-Bonin Arc was closer to the eastern side of the basin during the Miocene [Underwood *et al.*, 2010]. Strengthening of the NE directed Kuroshio Current during the Pliocene may have also affected the direction of suspended sediment dispersal [Underwood and Fergusson, 2005].

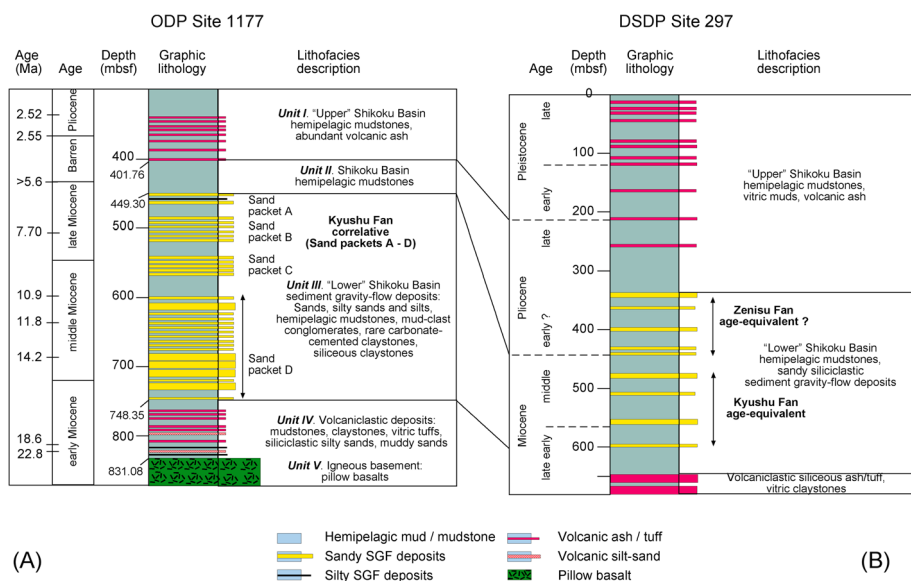


Figure 5. Summary lithologic logs for (a) ODP Site 1177 and (b) DSDP Site 297, also showing the approximate position of intervals of sand-rich sediment gravity flow deposits that are time equivalent to the Kyushu and Zenisu Fans at Site C0011 and C0012 as discussed in this paper (see Figure 1 for location). The inferred correlative sandy fans in IODP Sites C0011 and C0012 are also shown. Note that age dating at Sites 297 and 1177 is relatively poorly constrained compared with that at Sites C0011 and C0012.

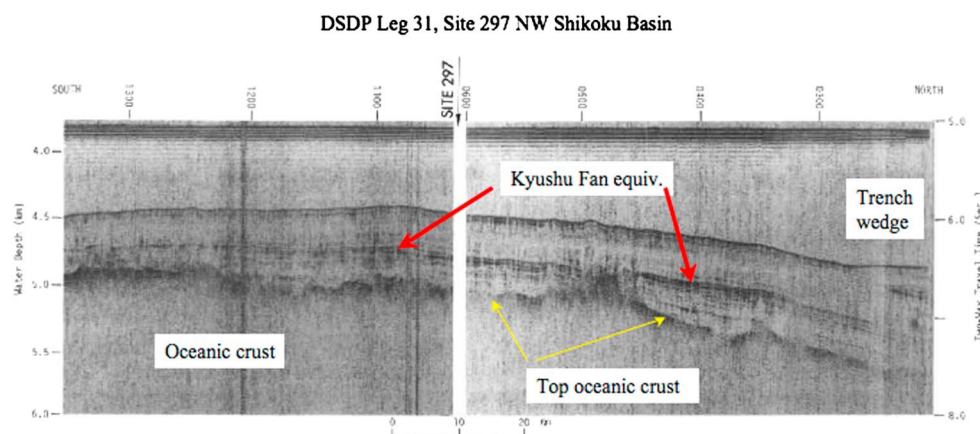


Figure 6. Seifu Maru (Maizuru Marine Observatory) reflection profile across the outer trench slope of the Nankai Trough and the NW Shikoku Basin through DSDP Site 297 (see Figure 1 for location). After *Karig et al.* [1975], the upper part of a 247 m thick unit of sandy sediment gravity flow deposits penetrated from 330 to 570 mbsf is shown by the arrow. Note the southward thinning and fining of the fan deposits (as inferred from their seismic character), believed to be coeval with the Kyushu Fan at Sites C0011 and C0012.

[29] To further constrain the sediment dispersal system, we have backtracked the paleogeographic positions of Sites C0011 and C0012 to ~12 Ma based on estimated plate convergence rates of *Kimura et al.* [2005] of 4 cm/yr to the NW from 0 to 4 Ma and 0.9 cm/yr to the NNW from 4 to 12 Ma (Figure 7). That restoration places the location during Unit V deposition ~350 km south of its present position.

8. Implications for Bathymetry of Nankai Trough and Tectonic-Stratigraphic Evolution of Shikoku Basin

[30] Plate reconstructions [*Mahony et al.*, 2011; *Hall*, 2012] essentially place the northern Shikoku Basin, both its western and eastern parts separated by the Kinan seamount chain, adjacent to the East China Sea. If these reconstructions are correct, then the older Miocene Kyushu Fan was most likely supplied its clastic material through a submarine canyon/s west of Kyushu in what is now the northern East China Sea and possibly from an area of the SW Japan Arc between Kyushu and Shikoku (Figure 7a). The continuity of the Shimanto, Sambagawa, and other tectonostratigraphic belts of SW Japan west of Kyushu to somewhere northeast of Taiwan [*Isozaki et al.*, 2010] does not, unfortunately, allow us to differentiate any further between these paleogeographic connections.

[31] A transport route through the East China Sea is supported by the presence of a very large and long-lived sediment drainage system immediately west of Kyushu that includes extensive submarine canyons

[*Oiwane et al.*, 2011, Figure 1]. At that time, the Okinawa Trough (Figure 7e) would not have blocked sediment delivery into the Shikoku Basin because that bathymetric obstacle did not form until 4–6 Ma [cf. *Kimura*, 1996; *Miki et al.*, 1990; *Lu and Hayashi*, 2001; *Yamaji*, 2003; *Expedition 331 Scientists*, 2010]. Also, within the Xihu depression (Figure 7e) in the central and northern East China Sea, basin inversion occurred during the late Miocene. The entire Tertiary succession of nearly 10,000 m thickness underwent inversion, with removal of up to 1600 m of sedimentary strata in the north [*Yang et al.*, 2011]. That erosional event probably contributed sediment influx to the Shikoku Basin.

[32] The Kyushu and Zenisu Fans were deposited when Sites C0011 and C0012 were positioned well to the south of the Nankai subduction front (Figure 7a). Broadly contemporaneous sands were drilled at DSDP Site 297 [*Karig et al.*, 1975] and ODP Site 1177 [*Moore et al.*, 2001a]. Those sediment gravity flow deposits were likely supplied from the same source area but through a more westerly supply route (Figure 7a). Coeval sands are not present, however, above the subducting basement high at ODP Sites 808, 1173, and 1174 [*Underwood*, 2007]. Blockage or deflection of flow paths by the Kinan seamount chain seems to demand separate transport routes to the Ashizuri transect sites versus the Kumano transect sites, split by the trend of the back-arc spreading ridge. Whether different submarine canyons supplied two coeval sandy fans or one route bifurcated on either side of the Kinan seamount chain remains unclear.

[33] The drainage systems that supplied the younger Zenisu Fans were probably similar to the present

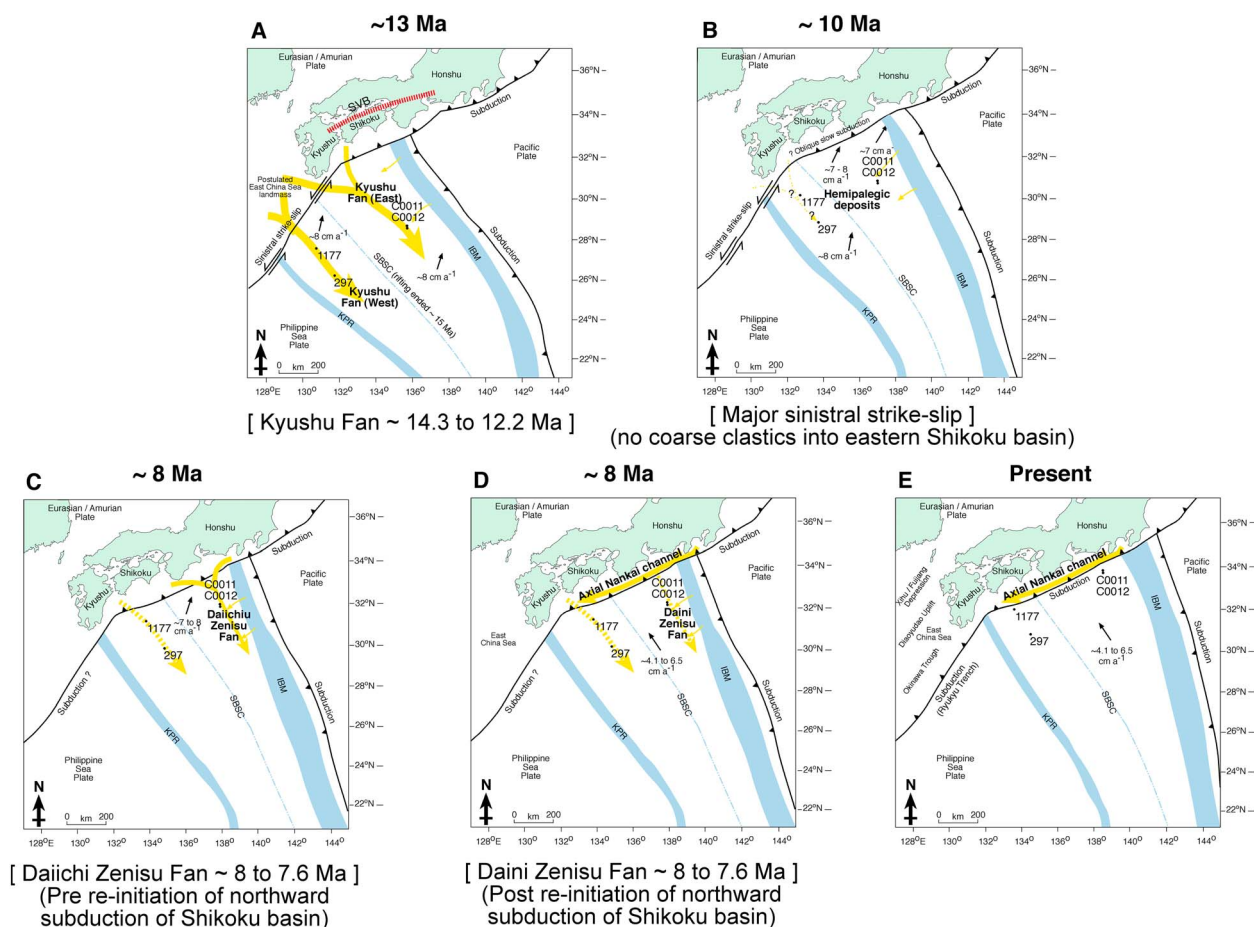


Figure 7. Schematic plate tectonic reconstructions for the Shikoku Basin and adjacent area, redrawn and modified from Mahony *et al.* [2011], to show the dispersal patterns for the coarse sandy sediments into the NE Shikoku Basin for (a) ~13 Ma, (b) ~10 Ma, (c) ~8 Ma immediately before renewed northward subduction, (d) ~8 Ma, immediately after renewed northward subduction, and (e) present day. Parenthesis shows more precisely the time indicated within that range for the paleogeography. Thickness of sediment dispersal arrows indicates the relative importance of multiple sources. IBM = Izu-Bonin-Mariana Arc; SBSC = Shikoku Basin Spreading Center; KPR = Kyushu-Palau Ridge. SVB = subduction-related Setouchi Volcanic Belt (12.4 to 14.8 Ma [Shimoda *et al.*, 1998; Kimura *et al.*, 2005]). Between 10 and 6 Ma, there is a lack of subduction-related volcanism [Mahony *et al.*, 2011; Tatsumi, 2006], with subduction and arc volcanism ceasing 1–2 Myr earlier. Note the change in coarse sediment dispersal at ~8 Ma, from submarine channels supplying sediment far out into the NE Shikoku Basin to axial trench (paleo-Nankai Channel), interpreted as the formation of a topographic trench as northward subduction of the Shikoku Basin oceanic crust resumed, picked up by arc volcanism 1–2 Myr later once the subducted slab had reached appropriate PTT (pressure-temperature-time) conditions. The plate boundary configurations used for the 2 to 15 Ma reconstructions of SW Japan utilized published finite rotation poles for the Philippine Sea plate relative to Eurasia from Gaina and Müller [2007]. In these reconstructions, Japan is held fixed and the latitude and longitude are for present day Japan.

(Figures 7b and 7c), i.e., from a paleo-Fuji River and/or from further west via a paleo-Shionomisaki Canyon and other submarine canyons [Kawamura *et al.*, 2009, Figure 1] or from multiple northern sources including the Izu collision zone via Suruga Trough. The Zenisu Fans were deposited during the later part of the so-called “slow subduction” tectonic stage of the Shikoku Basin below the SW Japan Arc (12 to 4 Ma), after sinistral strike-slip motion along parts of the plate boundary from 25 to 17 Ma [Kimura

et al., 2005]. The Mahony *et al.* [2011] reconstructions help explain an absence of subduction-related volcanism on Kyushu from 10 to 6 Ma, with increasing arc-like geochemistry after 6.5 Ma. They proposed sinistral strike slip off Kyushu as oblique subduction-accretion continued along much of the plate boundary with the Nankai Trough.

[34] Evidence for subduction-induced igneous activity was summarized by Kimura *et al.* [2005], who reinforced previous suggestions that anomalous

near-trench magmatism commenced suddenly during rapid opening of the Sea of Japan and continued from 17 to ~11–12 Ma. The opening of the Sea of Japan and clockwise rotation of the Outer Zone, therefore, coincide with deposition of the Kyushu submarine fan. This timing also matches a phase of rapid tectonic uplift in the Kyushu region (e.g., at ~11 Ma [Agar *et al.*, 1989]). The Setouchi Volcanic Belt, which extends for more than 600 km along the northern side of Shikoku (Figure 3a), records high-Mg volcanism caused by continued subduction of young and hot Shikoku Basin lithosphere between ~16 and 11 Ma [Kimura *et al.*, 2005]. We see no evidence to suggest that Shikoku Basin deposits were derived from the Setouchi volcanic source.

[35] Mahony *et al.* [2011] suggested that sinistral strike-slip motion offshore southern Kyushu continued from 15 to 6 Ma, later than that in the reconstruction of Kimura *et al.* [2005]. They also noted that the 10 to 6 Ma period is marked by a lack of arc-related volcanism in the Kyushu region which led Kamata and Kodoma [1994] to suggest a hiatus in rapid orthogonal subduction. In any plate reconstruction, however, subduction-triggered volcanism lags 1–2 Myr behind subduction initiation to allow the downgoing slab to reach appropriate pressure-temperature conditions for melting. Those aspects are factored into our paleogeographies (Figure 7). Renewal of orthogonal subduction off Kyushu at ~6 Ma, with an older subducting slab, probably led to the development of a bathymetric trench at the subduction front. Prior to that, however, the strike-slip or oblique slip character of the margin would be less likely to inhibit turbidity currents from flowing into the distal reaches of the Shikoku Basin.

[36] Channels of the Daiichi Zenisu Fan extended several hundred kilometers out into the Shikoku Basin, with length scales and dimensions similar to those of the present axial channel in the Nankai Trough (Figure 7) [Shimamura, 1989]. We see no evidence of large-scale levee development by aggradation but, rather, erosional-depositional channels (in the sense of [Normark, 1970]); i.e., there may be low-relief levee-overbank deposits not clearly imaged on the seismic line. The compelling evidence for these sediment gravity flows moving to the south comes from the petrography, not from the plate tectonic model or the seismic architecture; i.e., they contain terrigenous clastic material (above). The dimensions of these channels (hundreds of meters wide by several tens of meters deep), however, appear inconsistent with the small size of the Izu-Bonin islands, which would be less likely to sustain the required point sources of fluvial

discharge as compared to larger paleowatersheds of central Honshu, or from the East China Sea area.

[37] Underwood and Fergusson [2005] identified three major sand petrofacies from ODP Leg 190 sites: (1) volcanic lithic sand in the Quaternary trench wedge (Site 1174) that was transported by axial flow from the Izu-Honshu collision zone, (2) quartzose sand in the Pliocene to early Pleistocene accretionary prism (Sites 1175 and 1176) that was transported through transverse canyons and channels, and (3) sedimentary lithic sand in the upper Miocene sections (Sites 1177 and 1178) that were also derived from the transverse delivery systems [cf. Underwood and Fergusson, 2005, Figure 9]. The abrupt transition that we documented from the channelized Daiichi Zenisu sediment gravity flow deposits to the nonchannelized Daini Zenisu Fan occurred at ~8 Ma, which overlaps the time that the trench bathymetry began to form (~6 to 8 Ma in Taira [2001] and Taira *et al.* [1992]). Mahony *et al.* [2011] suggested that changes in the Philippine Sea plate motion at ~6.5 Ma led to more rapid, nearly orthogonal subduction beneath Kyushu, a model supported by an increase in arc-like geochemistry of lavas since ~6.5 Ma. They also favored initiation of Izu-Bonin and Honshu collision at ~8–6 Ma. After the plate boundary became a more prominent bathymetric low, channelized flows down the trench axis were more likely deflected westward by the seaward trench slope. Only larger-volume (thicker) flows, including volcanoclastic flows, appear to have overtopped the confines of the trench to continue for several hundred kilometers as sheet-like beds (Figures 7b and 7c). No other late Miocene or Pliocene channel systems have been documented in the northeastern Shikoku Basin, so we propose that this important tectonic event helped confine coarse clastics to the trench floor after sufficient relief was created.

9. Eustatic Control

[38] Two stratigraphic intervals at Sites C0011 and C0012 contain appreciable amounts of coarse clastic detritus. The older is dated 12.2 to 13.8 Ma (Kyushu Fan) and the younger Zenisu Fans are 7.6 to 9.1 Ma [cf. Underwood *et al.*, 2010]. These time intervals coincide with a prominent Neogene long-term fall in eustatic sea level as inferred from the oxygen isotope curve of Zachos *et al.* [2008] (Figure 8a). The Kyushu and Zenisu Fans can be correlated to the two inflection points on this long-term trend of accelerated cooling against a

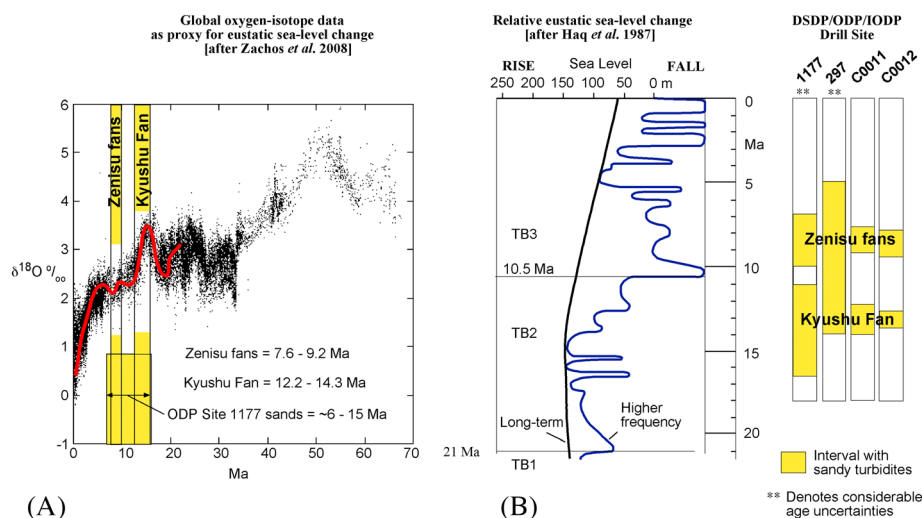


Figure 8. Timing of coarse sand supply into the Shikoku Basin at IODP Sites C0011 and C0012 and ODP Site 117: Site 297 is not shown as the age dating is relatively poor but appears to be similar to that in Site 1177. (a) Compilation of global $\delta^{18}\text{O}$ record from benthic foraminifera as a proxy for global climate, ice volume, and relative eustatic sea level change over the past 70 Myr. Data replotted from Zachos *et al.* [2008]. (b) Timing of sand supply in relation to the eustatic curves of Haq *et al.* [1987]. Supercycle sequences defined by Haq *et al.* [1987] are indicated as TB1, TB2, and TB3. See text for explanation.

long-term eustatic fall in sea level (Figure 8a). Comparable events are seen on the sea level curve of Miller [2011, Figure 4] and the oxygen isotope record of Cramer *et al.* [2009].

[39] The Haq *et al.* [1987] eustatic curves show two lowstands at 13.8 and 12.5 Ma that are consistent with the timing of sand transport into the Shikoku Basin, but there is also a substantial lowstand associated with a supercycle boundary (TB2/TB3) at 10.5 Ma (Figure 8b). Within the uncertainties of age dating, it is possible that sand accumulation continued into that time interval at Sites 297 and 1177 but not at Sites C0011 and C0012 where hemipelagic sedimentation occurred (Unit III). These differences can be reconciled with tectonic disruption of submarine canyon feeder system/s. The 8.2 Ma lowstand of Haq *et al.* [1987] is, however, consistent with sand accumulation at Sites C0011 and C0012 (Figure 8b), at a time when we believe that these sites were again linked to a submarine canyon feeder system/s. There is also a lowstand at 6.3 Ma, but by that time, the bathymetric depression of the trench was funnelling most of the terrigenous sand parallel to the trench axis.

[40] The synchronicity between some episodes of coarse clastic influx to the northeastern Shikoku Basin and some of the eustatic sea level falls inferred from the oxygen isotope proxy and Haq *et al.* [1987] curves suggests that glacioeustasy also exerted a significant influence on regional sedimentation. The absence of sands at Sites C0011 and C0012, when fine sand sediment gravity flow

deposits were accumulating at ODP Site 1177, likely reflects both the considerable distance of these latter sites from the Honshu Arc (~300 to 350 km south, based on realistic convergence rates as the Shikoku Basin crust was subducted) and that sand routing probably continued on the western side of the Kinan seamounts.

10. Summary and Conclusions

[41] Coring during IODP Expedition 322 showed how the depositional system of Shikoku Basin changed from an expanded (Site C0011) to a condensed section (Site C0012) in response to basement topography. Coring and logging also uncovered evidence of a previously unrecognized interval of late Miocene tuffaceous and volcanoclastic sandstones that we have designated the Daiichi Zenisu Fan (channelized, proximal) and immediately overlying Daini Zenisu Fan (sheet-like, distal). Older (early to middle Miocene) sediment gravity flow deposits with mixed detrital provenance (Kyushu Fan) are broadly correlative with superficially similar Miocene deposits at Sites 297 and 1177. Transport routes across the East China Sea must have extended ~300 km into the Shikoku Basin based on backtracking of known plate motion vectors. Geochemical and petrographic data from the pumice fragments suggest a provenance to the north in the SW Japan Arc. The change from channelized to sheet-like flows occurred at ~8 Ma. The

bathymetric low of the Nankai Trough probably formed at about the same time, but axial channels deflected sediment routing away from the NE Shikoku Basin. Thick pyroclastic flows were still capable of traveling several hundred kilometers beyond the confines of the trench to deposit sheet-like deposits. There is no petrographic evidence to support the dominance of an axial flow trajectory farther to the west at Sites 1175, 1176, and 1178 [Underwood and Fergusson, 2005]. Thus, trench-parallel sediment routing did not become regionally dominant until the Pleistocene, after the collision between the Izu and Honshu volcanic arcs.

[42] Sinistral strike slip probably dominated the western parts of the Nankai subduction system in the late Miocene. When combined with oblique subduction, that paleotectonic regime means that the accreted sediments of late Miocene age were likely derived from a sediment source in the East China Sea. A long (3 Myr) interval of hemipelagic deposition (Unit III) corresponds to a time when coarse clastic supply was cut off from Sites C0011 and C0012 during sinistral strike slip and oblique/slow subduction farther east. At least some sands entered the western part of the Shikoku Basin when only hemipelagic deposits accumulated at Sites C0011 and C0012 in the eastern part of the basin. Such a scenario would be expected at a strike-slip plate margin where canyon supply routes were being cut off to starve some fans of terrigenous sediment (e.g., the Kyushu Fan at Sites C0011 and C0012) and reconfigure sediment routing so that more westerly sites (297 and 1177) continued to receive terrigenous sediment from a now-eroded landmass in the East China Sea.

[43] While we postulate that deep marine clastic sedimentation was strongly influenced by tectonic adjustments along the western and northern margins of the Shikoku Basin, we also note that the sand-rich intervals broadly coincide in age with some of the prominent Neogene long-term glacioeustatic lowstands [Zachos *et al.*, 2008; Haq *et al.*, 1987]. The supercycle lowstand boundary shown on the Haq *et al.* [1987] eustatic sea level curves at 10.5 Ma does not express itself anywhere within the Shikoku Basin.

[44] Finally, recognition of submarine channels in the Zenisu Fan, as compared with more sheet-like submarine fan lobe deposits in the Kyushu Fan, means that potential migration routes for overpressured fluids will be different. For example, in sheet-like sands, pathways for fluid flow have greater horizontal permeability over hundreds to several thousand

meters when compared with channel sands. In addition, sand-filled channels, acting as stratigraphic asperities typically on length scales of hundreds of meters and thicknesses of many tens of meters, may localize strain and deform in different ways than sheet-like sand geometries. Also, an inspection of the seismic line (Figure 3) suggests that the décollement in the Kumano transect may be localizing in Unit II (Zenisu Fan), and therefore, it is important to characterize and understand this newly recognized Shikoku Basin stratigraphic interval.

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